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CATEGORIZATION OF CAD MODELS BASED ON THIN PART IDENTIFICATION

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ABSTRACT

Nowadays, industrial CAD models databases are becoming larger and larger, thus inaugurating new challenges for their management during the product design process. Unfortunately, neither the PDM nor PLM systems are good at indexing and sorting CAD models according to their content, and it is sometime more efficient to redesign a part than to try to find it in a database. Categorizing parts is a first step to solve this problem. This may allow both the re-use of the parts and the retrieval of the methods and processes adopted on them, thus avoiding wasting time restarting from scratch. In this paper, we focus on the characterization and classification of industrial parts with respect to the meshing issue, and notably the meshing of thin parts difficulty handled automatically and which often requires adaptation steps. The concepts of thin object and thin part are introduced together with the mechanisms and criteria used to identify such shape characteristics on CAD models. The final categorization results of a set of tests exploiting a normalized distance distribution associated to specific ratios computed from the bounding box surrounding the object to be classified. The proposed approach has been implemented and validated.

KEYWORDS

CAD models categorization, shape characteristics, thin features and objects, distance and shape distributions.

1. INTRODUCTION

Today, the methods and processes used all along the product design process end up with the generation and manipulation of a huge amount of digital data used to simulate the entire product lifecycle. In this framework, the geometric models are the intermediate representations shared by most of the actors. Therefore, large databases of CAD models are becoming available, thus inaugurating new challenges

for their management. For example, the complete digital mock-up of the airplane Airbus A400M is made up several hundreds of thousands of parts representing several terabytes of data.

Consequently, there exists an increasing need for indexing and sorting those elements to be able to retrieve them efficiently later on. Unfortunately, neither the actual PDM nor PLM systems are good at indexing and sorting CAD models according to their content, i.e. according to the shape. Indeed, it is not possible to find a part only with the filename, frequently unknown, or some annotations, possibly missing or limited for the specific purposes. Thus, the best method to retrieve a part is to exploit the shape characteristics. But, even the shape might be misleading or not enough. Depending on the purposes, we might be interested in parts, possibly very different in the overall shape, but similar according to some characteristics or behaviours. It is therefore necessary to provide tools enabling context-based shape categorization. Such a categorization can then provide a good mean for the re-use of past experiences and knowledge related to specific products or activities. In this paper, we are considering a categorization of the CAD models according to the meshing issue.

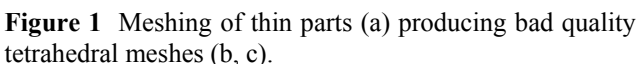
Product structural analyses are classically carried out following three steps: the CAD model definition, its meshing and the FE simulation including the boundary conditions specification. Before the meshing, the CAD model may also be idealized and simplified to remove unimportant features, i.e. features that will not affect significantly the simulation results. In this context, having tools to categorize parts according to the required types of adaptation could help the engineers in better and faster preparing their models to the meshing step. Actually, when meshing complex parts, two main steps have to be distinguished:

- the **adaptation step** aims at preparing the CAD models to the meshing and simulation while performing dedicated transformations. One example

- the **adjustment/repairing step** aims at improving the quality of the produced meshes while removing and/or repairing some badly meshed elements. This is a time-consuming step often performed manually using operations such as removal, swap, local refinement and so on.

However, the work exposed in this paper aims neither at preparing the CAD models nor at repairing the FE meshes. Again, the objective is to categorize CAD models to better anticipate the adaptation and repairing steps. In this way, designers spend more time to treat critical models on which thin parts have been highlighted. Using this approach, they can also look for already applied solutions by retrieving similar parts in huge databases.

ject categories is detailed in section 5. Finally, section 6 details the achievements and results we obtain using our prototype software.



The 3D shape retrieval has recently gained big attention due to the fact that large databases of 3D data are becoming available in various fields. Unfortunately, current methods for 3D shape retrieval are mostly focusing on the similarity of shapes from the form and structural point of views. Indeed, lots of shape matching methods exist [1-3, 8-9] and can be classified in three main categories: feature-based methods, graph-based methods and geometry-based methods (see figure 2). These methods have been implemented and tested. The results are more or less efficient but only when trying to retrieve a shape similar to the one of the query. Instead, to support a more application-oriented retrieval, we define a method to categorize parts with criteria not based on simple shape similarity but on specific shape distribution characteristics impacting on the meshing. Therefore our method can have impact in a concrete application in virtual mechanical engineering.

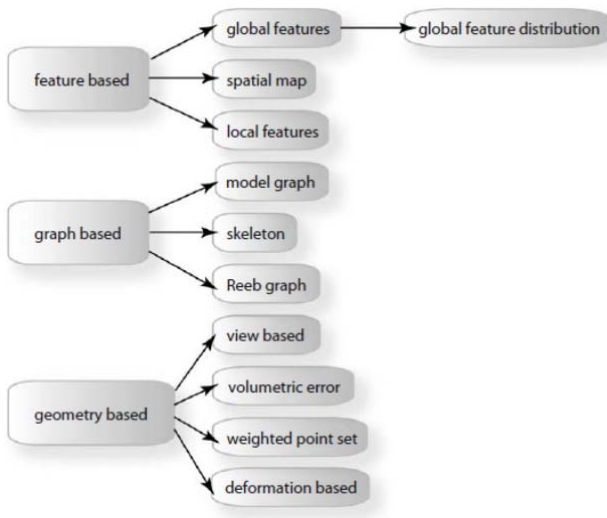


Figure 2 Taxonomy of shape matching methods [1].

In our approach, two steps can be distinguished. The first step consists in extracting shape distribution characteristics from a set of vertices obtained by discretizing the surfaces of the B-Rep CAD model to be categorized. The second analyses the descriptor values to determine the appropriate category for the considered object. Thus, our approach can be seen as belonging to the global feature distribution category (fig. 2).

Actually, the global feature distribution method consists in comparing the distribution of global features instead of the global features directly. Among the existing methods, the one of Osada et al. [4] introduces the so-called “D2 Shape Distribution” to represent, in a normalized histogram, the probability of occurrence of Euclidean distances between pairs of points chosen randomly on the skin of the object. This probabilistic approach is easy to implement, the computation speed is fast, and it is invariant to geometric transformations. As explained in section 4.1, this descriptor has been adapted to our needs.

However, such a distribution only characterizes the overall shape of the object and not the details. This is why the method is not sufficiently efficient to categorize parts with particular features. Therefore, we have been using another descriptor: the Oriented Bounding Box (OBB). The OBB (in opposition to axis-aligned minimum bounding box) is a descriptor introduced by Chang et al. [5] in an article suggesting some methods to compute it, like the most popular class of heuristic methods: the Principal Components Analysis (PCA). Because of its easy implementation and its good results for the considered parts, the most basic of the PCA-based methods has been adopted. Indeed,

when computing the bounding box, our aim is to get the volumetric ratio between the model and its minimal OBB. This indicates whether the object incorporate empty parts or not. We also use the dimensions of the bounding box to characterize some kind of features, as widely described in the following sections.

Finally, when considering the 3D models processing and retrieval methods [1-3], one can notice that they are working with a wide variety of 3D geometric representations (e.g. points cloud, polygons soup, structured meshes). However, most of the models found on the Internet are polyhedral models defined in a file format supporting the visual appearance. Today, the most common format used for this purpose is the Virtual Reality Modeling Language (VRML) format. Since this format has been designed for visualization, it only contains geometric and appearance attributes. In our approach, to be as much as possible independent of the adopted CAD software, we are working on polygons soups exported from in a stereolithography (STL) file format. STL models are not watertight meshes, i.e. they do not enclose a volume. So the algorithm developed is able to compute descriptors on a soup of triangles (polygons), thus it can easily deal with most of 3D models available over the web.

3. CONSIDERED OBJECT CATEGORIES

To define which categories of objects have to be considered, the different treatments and possible problems that can occur when meshing a CAD model have been analysed. In particular, three main categories of objects have been identified at first (fig. 3):

- the **globally thin objects** (fig. 3.a);
- the objects containing so-called **thin parts** much thinner than the rest of the object (fig. 3.b);
- the **normal objects**, i.e. those not belonging to the two above mentioned categories (fig. 3.c).

As discussed in the introduction, the first and second categories gather together CAD models that can be subjected to some idealisation processes and whose meshing may require manual adjustment steps. The second category also includes objects deserving particular attention for the choice of the mesh size. Today, the last category gathers together all the CAD models that do belong neither to the globally nor locally thin objects categories, despite the fact that their meshing can still be problematic. Therefore, in

the future, new categories have to be imagined to further categorize the actual “normal objects”.

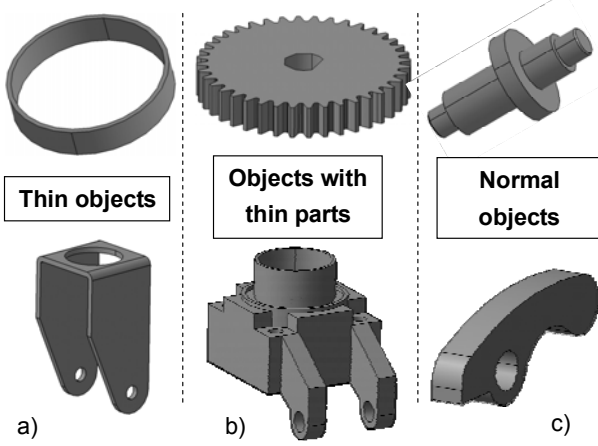


Figure 3 Examples of objects of the identified three categories: globally thin objects (a), objects with thin parts (b) and normal objects (c).

According to the characterizing features of the above classes, various existing shape descriptors have been analyzed and the most meaningful for their identification have been considered. They include the volume, the dimensions, and the thicknesses of the parts. The next section introduces the developed descriptors as well as the method used for their computation.

4. ADOPTED SHAPE DESCRIPTORS

4.1. Volume of the model

The method used to compute the internal area of a closed planar curve can be extended to compute the volume of a 3D closed B-Rep model. In 2D, the internal area of a closed curve can be computed while dividing the oriented bounding curve in several segments $[P_i P_{i+1}]$ (fig. 4). For each oriented segment, an oriented triangle $P_i P_{i+1} O$ is built using the origin O of the reference frame as third vertex. The signed area of those oriented triangles can be computed using a simple vector product (\wedge) as follows:

$$\text{Area}(P_i P_{i+1} O) = (\overrightarrow{P_i P_{i+1}} \wedge \overrightarrow{P_i O}) \cdot \vec{z} / 2 \quad (1)$$

The internal area of the curve is then computed by summing up the signed areas:

$$\text{Area} = \sum_i \text{Area}(P_i P_{i+1} O) \quad (2)$$

In 3D, the principle is similar. Instead of computing the area of oriented triangles, we sum up signed volumes of oriented tetrahedra. Each tetrahedron has a

base defined with an oriented triangle and the origin of the reference frame as forth vertex.

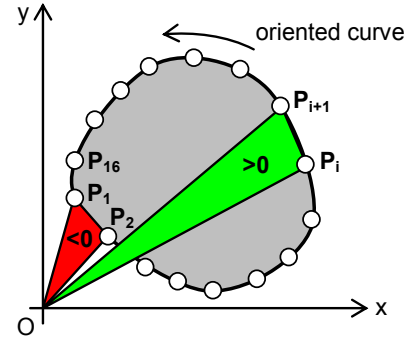


Figure 4 Computation of the area inside a closed curve.

4.2. Bounding Box

The first descriptor chosen from literature is the minimal oriented bounding box. It consists, given a finite set of N points, in finding the cuboid, i.e. rectangular parallelepiped, of minimal volume enclosing the set of vertices defined on the object surface.

To get this oriented bounding box, we decided to use a famous and basic but nevertheless efficient method which is the Principal Components Analysis (PCA). The PCA is mathematically defined as orthogonal linear transformation that transforms the data to a new coordinate system such that the greatest variance by any projection of the data comes to lie on the first coordinate (called the first principal component), the second greatest variance on the second coordinate, and so on. The principle of the PCA consists in computing the covariance matrix of the set of vertices. Then the three axes (vectors) of inertia are obtained by computing the eigenvectors of the covariance matrix. The last element is the center of gravity, whose coordinates (X_G, Y_G, Z_G) are the mean of the coordinates (X, Y, Z) of the set of points.

Given the three axis of inertia and the center of gravity of the model, the three dimensions of the bounding box can be computed. Indeed, the method consists in projecting all the points on the three axes of inertia, and then measuring the longest distance between projected points of the axis. It is done by creating, for each point of the model, a vector from the center of gravity to the point, and then by computing and storing in a list the dot product between these vectors and the three eigenvectors (normed vectors). From this list of oriented distances, the difference between the maximum and the minimum represents one distance of the bounding box. Then, with this information, it is possible to build the bounding box.

This bounding box is used in combination with the part volume as a descriptor giving information on the filling of the model in its bounding box. Also, the proportions among the dimensions of the bounding box reveal if the bounding box of the part is more like a plate (thin) or like a cuboid.

The combination of these descriptors is described in further details in a following section.

4.2.1. Enclosing surface area

The area of the model is used in the distance distribution, and is computed by summing the area of each triangle face of the model.

4.2.2. Distance distribution

One of the main descriptors used in our work is the distance distribution, inspired from the work of Osada et al. [4] on the D2 shape distribution descriptor. With this distribution, it is possible to characterize the overall shape of the object and to retrieve a similar shape. That means that the designer has to create its “categories” of models before being able to recognize a new one. In this work, the aim is to recognize features on subparts of the shape or on the entire shape. So, we have adapted the idea of computing distances inside the model, but with some conditions allowing us a characterization of the object features.

The aim of this descriptor is to compute the thickness inside the part. The main difference with the D2 shape descriptor is the fact that we compute distance between faces and not vertices and with some additional conditions. For each face of the model, the algorithm checks the parallelism between faces. Indeed, the distance between two faces needs to be defined when the two faces are not parallel. Thus, the developed algorithm acts differently according to the two cases: when faces are almost parallel, or when the angle between the two normals is less than 60° .

When faces are almost parallel, we first check if the faces are facing each other, and this to avoid irrelevant distance computations. We use a method which consists in projecting the three points and the center of gravity of one face into the other one. If the projection of center of gravity of a face lies inside the other face, like in figure 5.a, we consider that the distance computation is useful for the thickness distribution. Moreover, by using the opposite of the normal vector to the face for projecting the center of gravity, the algorithm allows the differentiation between parallel faces enclosing the object material or

the void. Indeed, we do not care of distance between parallel faces not enclosing the object material.

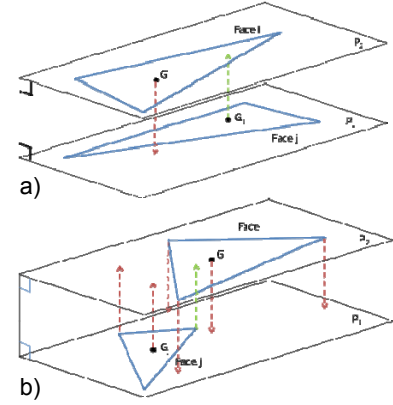


Figure 5 Parallel faces identification with projection of the gravity center of the triangle (a), and projection of the face vertices (b).

When no gravity center is projected in the other face, the algorithm verifies if at least the projection of one of the three vertices of the face is inside the other face (fig. 5.b). Actually, there is a case which is not taken into account, when the two faces are facing but all the projections (center of gravity and other points) are not lying in the other face. This is not a critical issue because we assume that if a triangle face f_i is in this case with a face f_j , f_i (or f_j) is almost parallel to a face adjacent to f_j (resp. f_i).

So the algorithm reviews each faces, one by one, and carries out the above tests before computing the distance. The distance is then evaluated by computing the dot product of the vector between the two centers of gravity and the outward-oriented normal vector of the tested triangle.

In case of non-parallel faces, i.e. when the angle between the two faces is between almost 10° to 60° , the considered distance is the smallest one between the three points of each faces. In this way, it is possible to recognize features as those in figure 3 where the thickness requires a check before meshing, then to categorize these parts and it is the purpose of next section. The values for distinguishing parallel from non-parallel faces have been heuristically chosen to get rid of approximation problems.

With these tests and this function, lots of irrelevant results are avoided. The distance distribution is then made tessellation-invariant by using the surface of the triangle associated to the distance: when the above described conditions are satisfied and a distance can be computed between a face f_i and a face f_j , the algorithm associates to the distance the area of

the faces f_i and f_j . At the end, all the areas associated to the same distance are summed and normalized by the value of the total object surface area. In this way it is possible to know how much surface (% of the total surface) is linked to the same thickness.

Figure 6 shows two examples of very simple parts with the associated thickness distribution function and the filling of their respective bounding boxes. The first model (fig. 6.a) is a cuboid with a rib, the percentage of the volumetric filling of its bounding box is equal to 0.74. The thickness distribution reveals only three distances inside the model. The x-axis indicates the value of the thickness divided by the diagonal of the bounding box, while the y-axis represents the area percentage. We decided to use the bounding box diagonal in order to make comparable objects of very different dimensions. The second model shows that also for very curved parts we can get meaningful values (fig. 6.b).

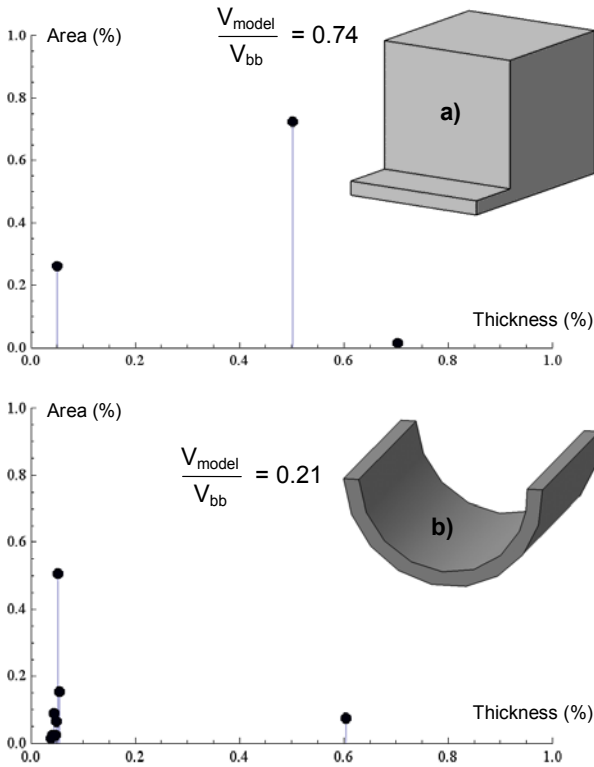


Figure 6 Examples of shape distribution functions.

5. PART CATEGORIZATION

In this section we illustrate how the descriptors introduced in section 4 have been used to define the membership function to categorize objects according to the classification described in section 3. This

membership function uses some thresholds which have been defined empirically (see section 5.3).

Let's define the different terms used in the following subsections:

- V_M : the volume of the model;
- V_{BB} : the volume of the bounding box;
- $D_{BB1}, D_{BB2}, D_{BB3}$: the dimensions of the bounding box so that $D_{BB1} \geq D_{BB2} \geq D_{BB3}$;
- $diag_{BB}$: the diagonal of the bounding box;
- $F[x; y] = z$: function of the distribution so that there is $z\%$ of the total area of the model associated to distances between $x\%$ and $y\%$ of the diagonal of the bounding box. For example, writing " $F[0; 0.25] = 0.88$ " means that "88% of the total surface is associated to a thickness between 0 and 25% of the diagonal of the bounding box".

5.1. Thin parts

The thin part class includes different types of objects, such as those similar to thin plates, or having an arbitrary shape with almost constant thickness distribution, or presenting a large emptiness of the bounding box (fig. 7). Different criteria are used to distinguish the typology of thin objects, as described in the following. Clearly, some thin objects can satisfy more than one criterion simultaneously.

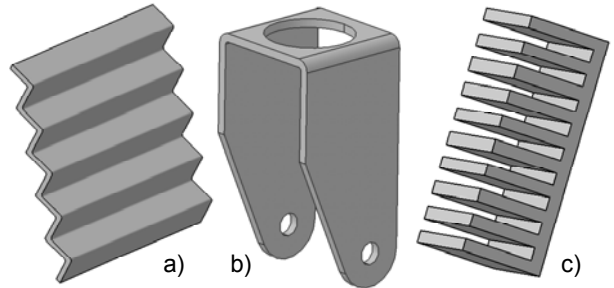


Figure 7 Examples of thin objects.

The first criterion (crit.1 in table 1) identifies plates, based on the fact that plate-like objects have one of the three dimensions of the bounding box quite small with respect to the two others, with a part filling at least the half of its bounding box. This criterion allows the identification of thin parts (fig. 7.a).

The second criterion (crit.2 in table 1) aims at considering thin objects having two of the bounding box dimensions quite similar while the third is rather small and including large part of material inside the part bounding box. Therefore, the conditions to be satisfied are: $(V_M / V_{BB} < 0.8) \& (D_{BB1} / D_{BB2} < 1.75) \& (D_{BB2} / D_{BB3} > 6)$. This means that parts in figures

7.a and 7.c are also kept by this criterion in the thin part class.

The third criterion (crit.3 in table 1) considers objects having a general overall shape with no predominant dimension of the bounding box and so that $V_M / V_{BB} < 0.2$. This kind of objects is characterized by the fact that the volume occupied by the part in the enclosing bounding box is just a small part (volumetric difference under 20%). The aim is to catch parts which are really extended in their bounding box, but with no volume, as the parts in figures 6.b, 7.b and 8.a. Indeed, the difference between the object in figure 8.a and the one in figure 8.b is that the first has no particular volume and has a quite constant thickness, while the second has some thin features colored in red. The criteria adopted are able to separate the second part from thin part class, and this is the topic of the next section.

The last criterion (crit.4 in table 1) considers the distribution descriptor and it is meant to identify thin parts whose volume is filling more than 20% of its bounding box volume. Here, the adopted formula is $F[0;0.25] > 0.6$ which allows us to classify objects like the one depicted in figure 7.c. It identifies a model that has a little filling of its bounding box but more than 60% of the total surface is associated to a thickness under 25% of the diagonal of the bounding box.

The thin parts category is not a class of parts necessarily difficult to mesh, but most of the time, a designer will have to be careful with these parts.

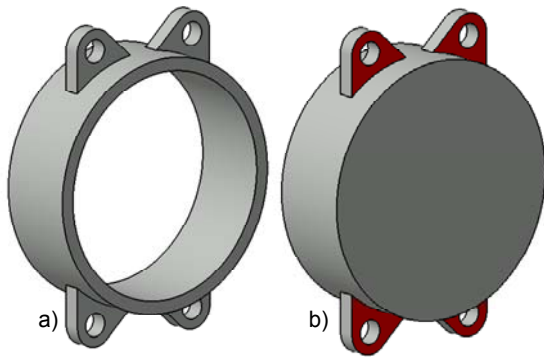


Figure 8 Examples of thin object (a) and an object with thin features (red surfaces) having a similar overall shape.

	BB filling	BB size rate	Distance distribution
Crit.1	$V_M/V_{BB} > 0.5$	$D_{BB2}/D_{BB3} > 12$	
Crit.2	$V_M/V_{BB} < 0.8$	$D_{BB1}/D_{BB2} < 1.75$ $D_{BB2}/D_{BB3} > 6$	
Crit.3	$V_M/V_{BB} < 0.2$		
Crit.4			$F[0;0.25] > 0.6$

Table 1 List of the criteria and thresholds adopted for the thin object classes.

5.2. Parts with thin features

This class includes all parts containing one or more features which may deserve some manual checks before their meshing. Indeed if the automatically proposed meshing size is too large, these features might be erroneously missed, thus giving rise to incorrect simulations.

Parts having thin features are characterized by areas having quite a small thickness with respect to the overall object thickness. Therefore they are recognized by mainly considering the distance distribution. Actually, when the part is not entirely thin, the thickness distribution detects a local thickness with respect to the rest of the part.

	BB filling	BB size rate	Distance distribution
Crit.5	$V_M/V_{BB} > 0.2$		$F[0;0.05] > 0$
Crit.6	$V_M/V_{BB} > 0.2$		$F[0.05;0.29] > 0$ $F[0.3;0.7] > 0.2$
Crit.7			$\min(d, \text{between non-parallel faces})/\text{diag}_{BB} < 0.05$

Table 2 List of the criteria and thresholds adopted for the objects with thin features.

Table 2 summarizes the defined criteria and thresholds used to detect parts with thin features. The first criterion and second criteria combine conditions on the volume with conditions on the thickness values. The first condition allows avoiding totally thin parts. The examples of objects classified according to crit.5 and crit.6 of table 2 are respectively given in figures 9.a and 9.b.

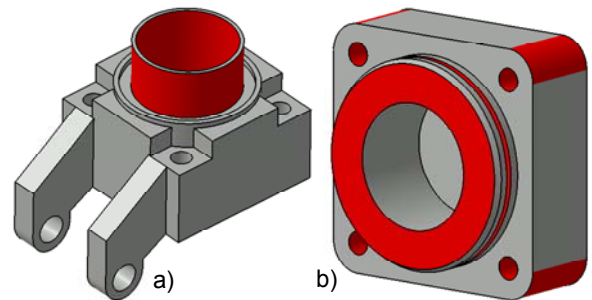


Figure 9 Examples of objects with thin features.

Finally, crit.7 is used to detect objects with thin features defined by non-parallel faces, as for gear teeth (fig. 2.b). Here, there is just a value of all-or-nothing and no distribution is compared. So, when faces with

an angle between 10 to 55° have a distance between them under 5% of the bounding box diagonal, the part is considered as a part with thin features.

5.3. Adopted thresholds

The thresholds adopted in the proposed criteria have been defined empirically after several trainings on multiple test cases. Actually, once the key parameters of those criteria have been identified, several trainings have been done and the thresholds returned by the experimented users have been averaged.

6. DEVELOPED PROTOTYPE AND RESULTS

The presented part classification has been implemented using Wolfram Mathematica [7] and integrated in Catia V5 with a Macro VBA. It has part of a larger project carried on in the LSIS laboratory on part classification in CAD databases. The Macro creates an info file associated to the classified part in which all the values of the various descriptors described in the previous section are stored. The values are computed using Mathematica. These data are the following:

- the ratio V_M and V_{BB} ;
- the dimensions of the bounding box D_{BB1} , D_{BB2} and D_{BB3} ;
- $F[0; 0.05]$, $F[0; 0.25]$, $F[0.05; 0.29]$ and $F[0.3; 0.7]$ which are three samples of the distribution function which are used in the further categorization;
- the indicator of existence of teeth-like thin features (0 or 1).

Storing these information allows a fast reclassification of the parts in case different thresholds are to be considered because more suitable for the types of meshing or simulations to be carried out. Actually, even if the chosen threshold values have been demonstrated to give quite good results on the set of considered parts, it is our believe that these thresholds might change according to the type of system used for meshing, therefore some learning techniques would be very useful to adjust the threshold to the specific engineering environment. Figure 10 shows the sequence of communication between Catia V5 and Mathematica.

The provided macro can be activated automatically or on user demand, on either a single model or on a set of models simultaneously. Actually, we foresee the possibility of automatically categorize a part

when it is designed, thus storing the computed info file as an accompanying document of each model, possibly in dedicated directory. The computed category information can then be used for making the simulation expert immediately aware of potential problems with the part and for supporting him to retrieve similar situations. This last capability can be supported only if all the already designed parts have been already classified, that's why we also consider the second possibility, i.e. classification of set of parts on user request.

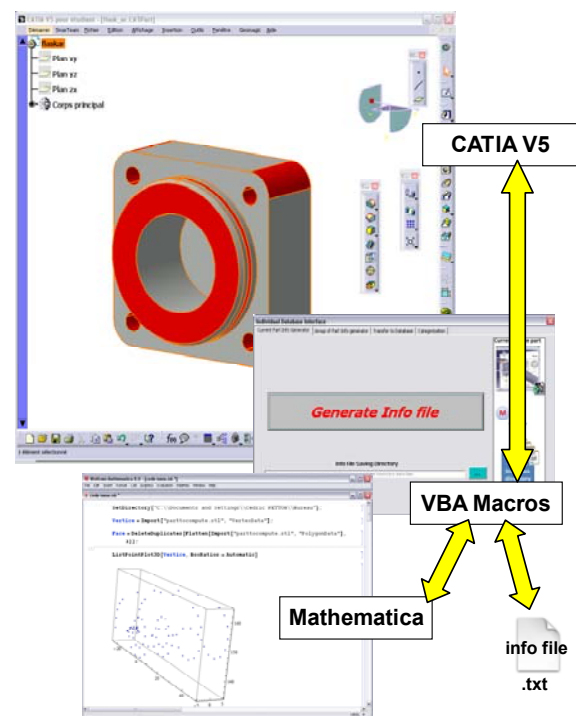


Figure 10 Sequence of communication between Catia and Mathematica through VBA Macros.

In order to support designers in using the classification tool, some graphical forms have been created allowing the user to interact with the system. They give him the possibility to launch the classification on the part under development or on all the parts in the database and to select the location of the info file generated. The location of the info file can be in another computer. Actually, we assume that each designer is operating on his/her own computer or has his/her own space on the network. Additionally, we have implemented the function that allows the retrieval of all the parts belonging to a specific category.

Since the aim of the macro VBA is to make an automated categorization on a large amount of CAD parts with no action of the designer, we made some experimentation to validate the accuracy of the algorithm.

In figure 11 the results of the proposed categorization algorithm is shown. As a conclusion, the experiment is that the criteria used for the categorization are generally working well.

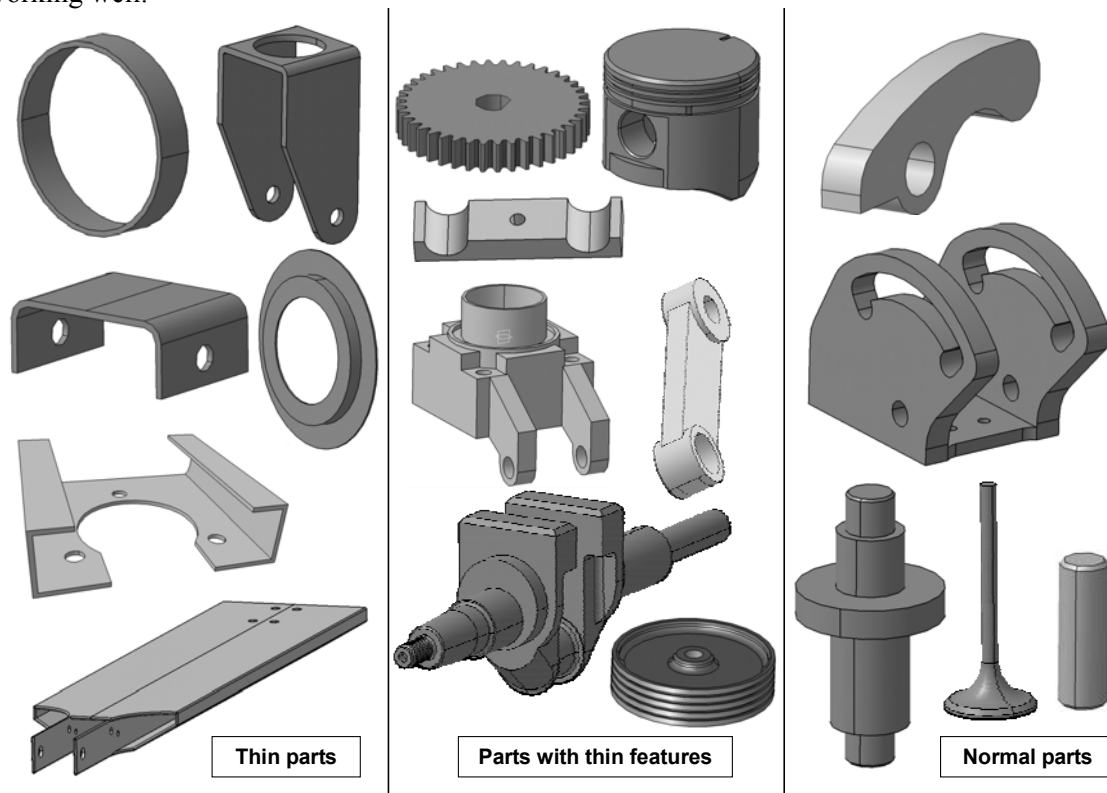


Figure 11 Categorization of thin parts, parts with thin features and normal parts

7. CONCLUDING REMARKS AND FUTURE WORK

The work presented in this paper is a first step towards the definition of a complete toolbox for the classification of parts which are potentially complex to mesh or not. Indeed, the main aim is still how to classify parts depending on their shapes and features. With the macro and the associated algorithm, all needed information is provided to the designer and the work of evaluation of the level of complexity during meshing is done for him/her, thus he/she can focus on other issues.

The prototype has been integrated within Catia, but working directly on the computed .stl file it is made system independent and then can be easily integrated on other commercial CAD systems adopted in companies. Additionally the use of the info file storing all the key shape descriptors and thresholds may allow a quick different categorization of the parts according to the user/system needs, being the most time con-

suming activity related to the shape descriptor evaluation.

Anyhow, the approach proposed is not exhaustive and additional criteria can be created to refine the categorization.

Current work includes the optimization of the algorithm to improve its efficiency and overcome the limits in the classification for the limited number of complex parts which are not well-classified. There will always be parts that the algorithm will not be able to treat, thus one of the possible future extension is the inclusion of some learning capabilities for both identifying the best threshold and descriptor combination.

In the future, we plan to work on returning additional information to the user on the shape elements corresponding to the thin areas. This would be used together with the already evaluated data in helping him in suitably modify the part and in selecting the most appropriate mesh size to use.

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